A HIGH-Q PERPENDICULAR BIASED FERRITE-TUNED CAVITY

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Summary

Rapid-cycling proton synchrotrons, such as the proposed LAMPF II accelerator, require approximately 10 MV per turn rf with 17% tuning range near 50 MHz. The traditional approach to ferrite-tuned cavities uses a ferrite which is longitudinally biased (rf magnetic field parallel to bias field). This method leads to unacceptably high losses in the ferrite. At Los Alamos, we are developing a cavity with transverse bias (rf magnetic field perpendicular to the bias field) that makes use of the tensor permeability of the ferrite. Modest power tests of a small (10-cm-diam) quarter-wave singly re-entrant cavity tuned by nickel-zinc ferrites and aluminum-doped garnets indicate that the losses in the ferrite can be made negligible compared with the losses due to the surface resistivity of the copper cavity at power levels from 2 to 200 watts.

Introduction

The use of ferrites in cavity tuning is not a new idea. As early as 1956, several groups[1-3] had successful experimental results and had developed a theoretical understanding of ferrites in rf fields. These early experiments used ferrites with a bias magnetic field applied perpendicular to the rf magnetic field in their cavities. They also tried placing the bias direction along other possible axes of their cavities. All these experiments were carried out at X-band (approx 10 GHz). In all the cases of applied magnetic field perpendicular to the rf magnetic fields, the applied bias was less than the needed bias to cause the gyromagnetic resonance. These experimenters were hampered by the poorer quality of the materials they used.

Accelerator cavities have been tuned with ferrites in many laboratories. Some examples are the CERN PS, the Brookhaven AGS, and the rings at Fermilab. In all these facilities, ferrite tuning is achieved by having the applied bias magnetic field parallel to the rf magnetic fields in the cavities. The variation in cavity frequency is achieved by varying the μ of the ferrite by moving along the hysteresis loop of the ferrite.

The many disadvantages of ferrite tuning include: low cavity Q, heating problems in the ferrite, and high maintenance. All of these problems are caused by the high loss most ferrites exhibit in rf cavities. A low-loss ferrite-tuned cavity was built for the Los Alamos Proton Storage Ring[4] using a newer ferrite material. The applied bias magnetic field is perpendicular to the rf magnetic fields and the cavity is operated in the region above the gyromagnetic resonance. Selecting the right ferrite can lead to the condition of a high-Q resonant cavity that can be tuned in frequency over a large range with no appreciable losses in the ferrite.

Perpendicular Bias Magnetic Field Theory

Perpendicular bias is used in ferrite devices today for a variety of microwave uses. These devices include isolators, circulators, phase shifters, attenuators, and filters. These devices have their properties derived from the gyromagnetic resonance phenomena.

If we have the condition of a magnetic dipole in a ferrite subjected to a dc magnetic field H and next apply a second magnetic field h which is both an rf field and perpendicular to the dc field, the rotating vector (H + h) describes a cone. The magnetic moment M moves with a precessional motion around the cone. The condition of gyromagnetic resonance occurs when the rf frequency is synchronized with the precession. The resonance condition occurs at

$$H_0 = f/2.8 \quad ,$$

where H_0 is the dc magnetic field in oersteds and f is the rf frequency in MHz.

One must remember that under these conditions the representation of the permeability of the ferrite is a tensor quantity. The permeability tensor was derived by Polder and is expressed as[5-6]

$$\bar{\mu} = \mu_0 \begin{bmatrix} \mu_x & -jk & 0 \\ jk & \mu_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad ,$$

where the dc magnetic field is applied in the z direction and the material is saturated in the z direction. The permeability of the ferrite has both a dispersive and a dissipative component and can be written as

$$\mu = \mu' - j\mu'' \quad .$$

Figure 1 shows an idealized plot of permeability versus applied dc magnetic field. The plot of μ'' is the dissipative component, and the greatest loss occurs at an applied field H_{RES}, which is the condition for gyromagnetic resonance. The plot of μ_e is the effective μ for the dispersive part of the permeability μ'. The value of μ_e is varied depending on the relation between the direction of wave propagation in a cavity and the dc magnetic field. The cavity frequency is tuned in the optimum way by varying the dc bias from H_2 to H_1, thus varying the μ_e from μ_2 to μ_1. In the region above resonance, the value of μ'' is lowest. In selecting ferrite, care should be taken to choose a material that has the lowest μ'' above resonance. Materials with low values (1.5-2.5 Oe) of ΔH_k (spin-wave line width) should be chosen. Thus, a large variation in μ_e can be reached under a very low-loss condition.

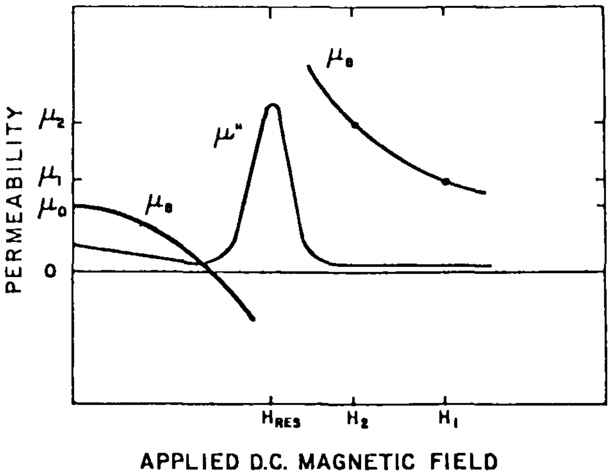

Fig. 1. Plot of permeability vs applied dc magnetic field.

Prototype Ferrite-Tuned Cavity

I. Description

A prototype cavity was built near the suggested frequency of 40-50 MHz for the proposed LAMPF II synchrotron. The prototype cavity is shown in Fig. 2. It is a quarter-wave coaxial cavity with ferrite loading on the low-voltage end. The solenoid provides an axial dc magnetic field, whereas the rf magnetic fields of the cavity are in the θ direction. The solenoid was capable of providing dc magnetic fields up to 3500 gauss. The aluminum-doped garnet material (TDK Y5) has a low-value spin-wave line width of 1.6 Oe. While the more commonly use nickel-zinc ferrite (TDK G102) has a spin-wave line width of 5.4 Oe. Also, the saturation field of the garnet is only 600 gauss as compared to 5100 gauss for the nickel-zinc material.

II. Experiments

Experiments were performed with approximately 5.0% ferrite loading by volume. The ferrites were in the form of toroids of dimensions 2.54 cm thick, 5.08 cm inside diameter and 9.14 cm outside diameter. There was a 0.32-cm region between the inner conductor and the ferrite toroids that was filled by teflon spacers. The diameter of the outer conductor was 10.2 cm. The solenoid had a region of uniform field large enough to handle the ferrite volume. Figure 3 shows the results for the ferrites with frequency being plotted versus dc magnetic field. Figure 4 shows the same materials plotted now with loaded-cavity Q vs frequency. Results are shown from modest power test between 2 and 200 watts into the test cavity. Care was taken to insure that the reflected power was less than 10%. The plots show that over a 6% tuning range the low power (2 watts) ferrite-loaded cavity Q is the same as the modest power (200 watts) measurements. These tests are still at least one order of magnitude away from working the ferrite in a manner similar to that of a real high-power cavity.

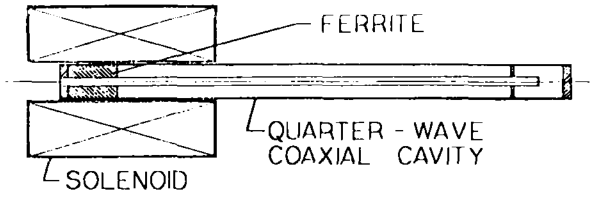

Fig. 2. Drawing of prototype test cavity.

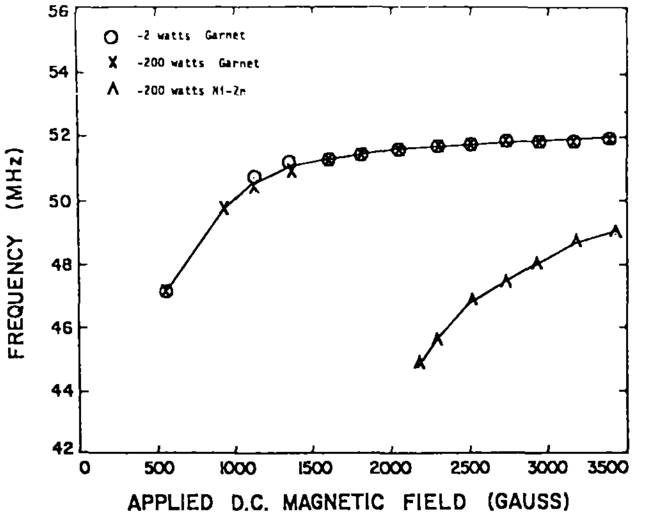

Fig. 3. Results for ferrites with frequency plotted vs dc magnetic field.

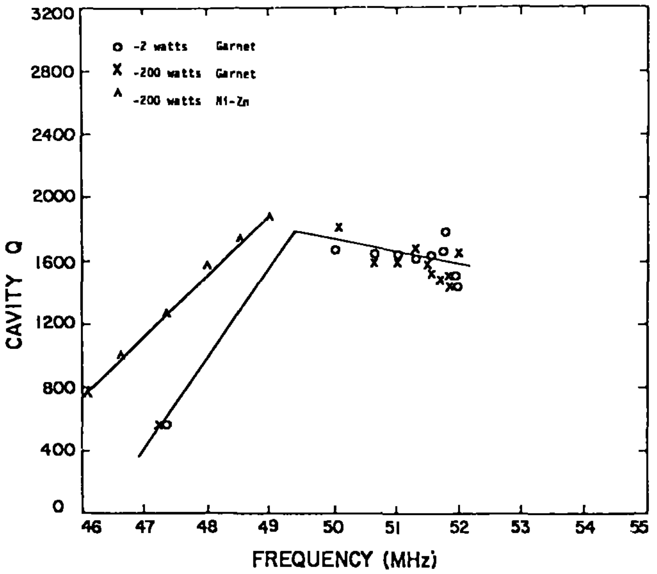

Fig. 4. Results for the ferrites plotted as Q vs frequency.

Conclusion

Results from these tests on a ferrite-tuned cavity using transverse bias are very encouraging. A high Q has been achieved over a large tuning range for several different ferrites. In order to achieve the 17% tuning range needed for LAMPF II, a larger ferrite volume will be needed. It is reasonable to expect that this tuning range can be reached in the high-Q region. However, there is another consideration when using garnet material. The cost per unit volume of garnet material is roughly four times that of nickel-zinc. Therefore, the garnet material has to substantially out perform the nickel-zinc to make it attractive.

References

1. G. R. Jones, J. C. Cacheris, and C. A. Morrison, "Magnetic Tuning of Resonant Cavities and Wide-Band Frequency Modulation of Klystrons," Proc. IRE 44, 1431 (1956).
2. C. E. Fay, "Ferrite-Tuned Resonant Cavities," Proc. IRE 44, 1446 (1956).
3. C. E. Nelson, "Ferrite-Tunable Microwave Cavities and the Introduction of a New Reflectionless, Tunable Microwave Filter," Proc. IRE 44, 1449 (1956).
4. L. M. Earley, G. P. Lawrence, J. M. Potter, and F. J. Humphry, "A Resonantly Coupled, Ferrite-Tuned Buncher-Cavity System for the Los Alamos Proton Storage Ring," 1982 IEEE MTT-S Int. Microwave Symp., June 1982, p. 246.
5. L. Thourel, The Use of Ferrites at Microwave Frequencies (Pergamon Press, Macmillan Co., New York, 1964).
6. B. Lax and K. Button, Microwave Ferrites and Ferrimagnetics (McGraw-Hill, New York, 1962).